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AN ORBITAL FACILITY FOR LOW GRAVITY FLUID MECHANICS EXPERIMENTS

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ABSTRACT

A rotating, cable-connected space laboratory for conducting extensive low gravity fluid mechanics experiments is described. The advantages of the various types of existing experimental facilities are discussed in terms of the proposed facility. Existing low-g sloshing data are reviewed. The additional information needed is outlined, and a series of experiments for obtaining this information is proposed.

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RESEARCH AND DEVELOPMENT OPERATIONS

DEFINITION OF SYMBOLS

Symbol	Definition
a	tank radius
B_o	Bond number, $(\frac{ga^2}{\sigma/\rho})$
g	imposed acceleration level
g_o	acceleration due to gravity at sea level
h	drop height
t	free fall time
η_w	slosh amplitude at the wall
ρ	fluid density
σ	fluid surface tension
ω	rotation rate of orbital test facility
$\omega(0)$	rotation rate for zero cable length

TECHNICAL MEMORANDUM X-53561

AN ORBITAL FACILITY FOR LOW GRAVITY FLUID MECHANICS EXPERIMENTS

SUMMARY

A rotating, cable-connected space laboratory for conducting extensive low gravity fluid mechanics experiments is described. The advantages of the various types of existing experimental facilities are discussed in terms of the proposed facility. Existing low-g sloshing data are reviewed. The additional information needed is outlined, and a series of experiments for obtaining this information is proposed.

I. INTRODUCTION

In the past, problems relating to the dynamics of liquid propellants in the tanks of space vehicles have occurred during the boost phase of flight where body forces caused by vehicle accelerations predominate. More recently, with the introduction of large upper stages designed to restart after an extended period in orbit, interest in liquid propellant dynamics under low g has increased. Since the predominant force disturbing the vehicle attitude is expected to arise from propellant sloshing, the sizing of the attitude control engines and their propellant supply cannot be done properly without an accurate low g slosh model. This is especially true for long duration missions, since errors in propellant consumption predictions will tend to accumulate. For these and other reasons, it is expected that the dynamics of liquids in the low gravity environment will have an important effect on the control of the space vehicle during orbital coast, transplanetary coast, docking, and refueling maneuvers.

II. AVAILABILITY OF INFORMATION

The body of knowledge concerning any physical phenomenon is composed of experimental observations and analytical formulations. Neither of these parts is sufficient alone; they complement each other. Experimental data are necessary if mathematical models are to be formulated and verified, but if a completely experimental approach is taken, the amount of testing involved soon becomes prohibitive.

Low gravity experiments in fluid dynamics have been conducted using three techniques: very small models under one "g"; free-fall facilities; and flight tests. A fourth technique, canceling the gravity forces with a magnetic field, has been proposed. Table 1 contains a summary of typical ground-based facilities for simulating low gravity conditions. Only three drop towers are listed in table 1, but these are representative of the facilities in operation in this country. The largest is the MSFC drop tower, which has a free-fall period of approximately 4 1/2 seconds and accommodates models with diameters up to 15 cm. The North American Aviation tower is representative of most privately owned facilities [1], while the Lewis double pass drop tower represents the most sophisticated concept yet to be developed. Drop towers have the advantage of being relatively inexpensive; their major disadvantage is the very short test time afforded. If drag is disregarded, the free-fall time produced is given in terms of drop height, h, and acceleration due to gravity, g_o, by the expression $t = \sqrt{h/g_o}$. From this relationship, we can see that very great heights are necessary if more than a few seconds of free fall are to be produced. Another type of free-fall facility uses an aircraft flying a parabolic arc. Several types of aircraft have been used for this purpose, the largest being the KC-135, which is capable of approximately 32 seconds of free-fall time [2]. This type of facility is subject to random disturbances, making it difficult to control the test conditions. From a study of free-fall facilities in general, it appears that a test time of approximately 35 seconds is the limit, if the falling body is not to exceed Mach number 1.0.

Tests using very small models under one "g" (bench testing) have been made by several investigators (see, for example, References 3 and 4). In these tests the tank size is scaled so that the ratio of capillary forces to gravity forces is the same for the model and the prototype. While this procedure affords very long test periods, there are certain disadvantages associated with very small tanks. There may be some large viscous effects present in small tanks which would not be significant in a much larger tank. In addition, several investigators have experienced difficulties with impurities or films on the walls of very small tanks which significantly altered the dynamic characteristics of the fluid. Still another technique for testing at one "g" uses a magnetic field to cancel the gravity forces. This method has not yet been used for any experiment involving fluid dynamics, and some potential difficulties are expected. In summary, ground test facilities are not yet capable of providing long test periods in tanks of reasonable size.

A number of low gravity experiments have been flown aboard suborbital and orbital space vehicles. Table 2 presents a summary of these data. Several of these tests involved full size vehicles instead of models. This was true of Centaurs 4 and 8 [5] as well as AS-203 [6]. Data from such tests, while useful, are primarily intended to verify design. The experiments on board MA-7 and the WASP flight were more

scientific, but were still rather unsophisticated. All of these flight tests had important shortcomings in the areas of instrumentation and data retrieval. To date, no rigorously controlled, fully instrumented experiment or series of experiments has been conducted in earth orbit. All of the tests have been designed to provide qualitative rather than quantitative results.

Figure 1 summarizes the data presently available from flight and ground-based experiments. The dimensionless amplitude ratio, η_w/a, is a measure of the magnitude of the slosh. The Bond number, which is the ratio of gravity to capillary forces, indicates the degree of weightlessness (low Bond number, low gravity). Experimental data for damping, forces, and frequencies are indicated by the shaded areas. Because the slosh amplitude is a function of many variables, it is difficult to estimate values for future vehicles. For Bond number, however, some approximate numbers are available. The S-IVB stage of the Saturn V will operate in the Bond number range from 65 to 100. A manned Mars vehicle, with nuclear propulsion, would operate in the Bond number range from 50 to 0.5. Smaller vehicles might have Bond numbers ranging down to 0.1.

Analytical solutions for the liquid natural frequencies and mode shapes are at present available for only a few specialized cases, and solutions for the forces, moments, and damping have not yet been found for any case. Table 3 shows the analytical tools presently available for dealing with low g slosh. All the theoretical work to date has been concerned with flat-bottomed cylindrical tanks, since they represent a fairly simple geometric configuration. For axisymmetric (longitudinal) free oscillations, two independent investigators, Fung [4] and Benedikt [1], have obtained solutions for frequency and mode shape. In the case of anti-symmetric sloshing, Satterlee [3] has obtained solutions for the natural frequency, but not the surface wave shape. For axisymmetric forced oscillations, Fung has developed expressions for the frequency and mode shape. No solutions or formulations including the effect of capillarity have been developed for the nonlinear or large amplitude case. Solutions for the frequencies, forces, moments, and damping must be obtained if an accurate dynamic model for low g slosh is to be derived.

III. NEEDED EXPERIMENTAL DATA

As discussed in the preceding section, a certain amount of experimental data is required to complement every theoretical analysis. Experimental data are necessary to verify the solutions to the low g fluid dynamics equations. The effects of Bond number, Reynolds number, nondimensional wave amplitude, and baffle geometry on slosh frequency,

induced force, and damping ratio must be determined for three basic tank configurations: unbaffled flat-bottomed cylinder, baffled flat-bottomed cylinder, and unbaffled sphere. To obtain these results tests should be conducted in tanks of three different diameters. Since approximately 20 cycles should be allowed for the decay of transients before the actual measurements are taken and another 20 cycles are required for recording the data, a total of 40 cycles of forced oscillation would be required for each test. The driving mechanism used should provide continuous, sinusoidal motion and have provisions for changing both the amplitudes and frequency of excitation. Instrumentation should be provided for measuring the forces and moments exerted by the sloshing liquid, slosh amplitude, driving frequency, and driving amplitude. In addition, visual records in the form of television or motion pictures should be taken. The variation in Bond number and Reynolds number should be obtained through the variation in tank size and imposed gravity level. The nondimensional wave amplitude should be varied by changing the forcing amplitude and frequency. For determining the effect of baffle geometry, both baffle width and depth should be varied.

IV. POSSIBLE SOURCES OF FUTURE EXPERIMENTAL DATA

Future possibilities for ground testing are not very promising. This is mainly because of the very short times available with tanks of reasonable size, and since, for a given test, the required time varies with the model tank radius to the three-halves power, little chance for improvement is possible. Tests in very small tanks could be useful if enough data were available from larger tanks to accurately assess the viscous effects.

Orbital experimentation is more promising for future work. This type of facility can provide a very low level of gravity for an extended period of time. If a rotational concept is used for producing the artificial gravity required, an easily controlled uniform test environment can be produced with a minimum expenditure of propellant. If a man is included as an observer and mechanic, the advantages of flexibility and reliability can be added.

V. PROPOSED EXPERIMENT

The proposed low "g" test facility will be made of available vehicle hardware in orbit, in particular, a spent S-IVB-IU-SLA.

The design of the rotating test facility was based on the following ground rules: one percent maximum variation in g level throughout the test fluid; .0025 g's at a distance of 150 feet (45.7 meters) from experiment to the center of rotation. The g level was chosen to give a Bond number in the middle of the region of greatest interest. The one percent maximum variation in g level with a 1-foot (.3048 m) tank requires the experiment to be at least 100 feet (30.48 m) from the center of rotation.

To have the experimental package at a minimum distance of 100 feet (30.48 m) and, at the same time, be able to vary the acceleration environment at the experiment location, the experimental package is located in the SLA, which in turn is connected by a long cable to the S-IVB-IU combination. (The basic configuration is given in figure 2.) The entire system is given an initial angular momentum with the SLA connected to the S-IVB-IU by firing the APS engine on board the S-IVB. The cable is then released allowing the SLA with the experiment inside to move out to the proper location.

Figure 3 shows experiment packages mounted on lightweight tubes inside the SLA. The packages would be located near the SLA center of gravity to minimize the effects on the experiment of any SLA roll or wobble. The strength requirements for the mounting tubes would depend on the forces occurring during boost, since the forces during the experiment would be small.

The performance of this facility was based on the following parameters:

	Weight	Inertia
S-IVB & IU	$854 \ \frac{\text{lb - sec}^2}{\text{ft}}$	331,780 lb ft-sec^2
SLA	$109.6 \ \frac{\text{lb - sec}^2}{\text{ft}}$	11,522 lb ft-sec^2.

The obtainable acceleration level range is given in figure 4. With an initial angular velocity of .15 rad/sec, the acceleration environment varies from .0068 g's at a distance from the experiment to the center of rotation of 100 feet (30.48 m) to .00036 g's at a 300 foot (91.44 m) distance.

The cable tension variation under these conditions is given in figure 5. Based on the information in this figure, it was decided that a .0625-inch (.1587 cm) diameter blue center steel hoisting rope with a breaking strength of 360 lb (1600 n) could be used as the cable. (The angular velocity variation can be obtained from figure 6.) With an initial angular velocity of .15 rad/sec, the final velocity is .0063 rad/sec at 300 feet (91 m).

The primary advantages of this facility over the direct thrust type of orbital low g test facility (such as Project Thermo [7]) are the long test time at a given acceleration level and the ability to vary acceleration level over a wide range. Both of these conditions can be obtained with no expenditure of propellant once initial angular momentum is given the system. The propellant required to give the system a prescribed initial angular velocity is given in figure 7. For the proposed test, an initial angular rate of .15 rad/sec can be obtained with approximately 20 lbs (9.072 kg) of APS propellant on board.

The fluid mechanics experiments are designed to furnish basic scientific information dealing with the dynamics of liquids under the influence of weak gravitational forces; they are expected to constitute an important contribution to the technology required for future space activities. The primary areas to be investigated deal with the determination of (1) the natural frequencies and mode shapes, (2) the forces and moments exerted on the container by the fluid, and (3) the damping provided by various baffle configurations. In these areas this program is designed to verify and extend existing data from ground facilities while providing previously unobtainable results on phenomena such as damping. The fluid mechanics regimes pertinent to propellant oscillation problems are best described in terms of two dimensionless products, Bond number and amplitude ratio. Figure 1 outlines the area to be investigated in terms of these parameters. The variation in Bond number is slightly greater than one order of magnitude and covers the range of principal interest for large propellant tanks.

It is proposed that the experiment consist of independent experiment packages or modules, one for each combination of tank shape, baffle configuration, and test liquid. This modular concept would allow changes in the scope of the experiment by addition or deletion of experiment packages. Data could be recorded for all experiment packages simultaneously at each acceleration level; this would result in a saving of experiment time as compared to a set-up requiring configuration changes.

A typical experiment package is shown in figure 8. It contains a 12-inch diameter tank and a 6-inch diameter tank mounted by means of load cells to a carriage. The carriage is driven in a reciprocating motion on three rails by a small motor and yoke mechanism. (Other methods of getting liquid oscillation are shown in figure 9.)

The camera is also mounted on the carriage so that it moves with the tanks. Two mirrors are placed in such a way that the camera views both the front and side of each tank. A television camera would be required for monitoring the experiment and a record of the experiment could be made on video tape. Each experiment package would weigh approximately 100 lbm.

The tank shapes of primary interest are cylindrical and spherical as shown in figures 10 and 11. Most of the theoretical work to date is for these basic configurations and the results of the proposed experiment would provide a check for this theoretical work. The effect of baffle width could be investigated using an adjustable iris baffle as pictured in figure 10.

Ethyl alcohol and olive oil are proposed as test fluids. For a particular tank size and acceleration level, the difference in Bond number for these liquids is small (figure 12), but there is nearly an order of magnitude difference in Reynolds number (figure 13). Tests using these liquids at the same Bond number could be used to determine the importance of Reynolds number in low gravity fluid dynamics.

A number of interesting and valuable experiments could be performed using this facility. However, there are several objectives which may be considered most important. These can be listed as follows:

(1) The effect of Bond number and Reynolds number on slosh frequency, induced force and damping for an unbaffled cylindrical tank.

(2) The effect of Bond number and Reynolds number on slosh frequency, induced force and damping for a baffled cylindrical tank.

In addition to these objectives, there are several others which might be termed highly desirable. These can be listed as follows:

(3) The effect of amplitude upon slosh frequency, induced forces, and damping in baffled and unbaffled cylindrical tanks.

(4) The effect of baffle width and fluid depth upon damping in baffled cylindrical tanks.

(5) The effect of Bond number and Reynolds number on slosh frequency, induced force, and damping in baffled and unbaffled spherical tanks.

This does not exhaust all the possible experiments, but the information thus obtained is expected to constitute an important contribution to the technology required for future space activities. For the purpose of discussion consider objectives 1 and 2. Two modules using ethyl alcohol, one baffled and one unbaffled, and two modules using olive oil, one baffled and one unbaffled, would be required to meet these objectives. The total weight for this system would be approximately 400 pounds. The current test plan calls for simultaneous tests in all four modules.

Table 4 shows the proposed test program. Tests will be conducted at seven specific g/g_o levels yielding a Bond number range from 55 to .67. Table 5 presents an in-depth look at one particular test and the runs required. Seven runs will be made to accurately fix the natural frequency. The frequency increment between these, as well as the forcing amplitude, were picked using the preliminary results obtained by Southwest Research Institute. The time required per run is based on a total of 40 cycles of which approximately 20 will be required to establish steady state conditions. Objectives 3 and 4 could be accomplished using the same test modules, if desired. Objective 5 would probably require two additional modules.

Objectives 1 through 5 listed above could be accomplished using 6 modules similar to the one shown in figure 8. This would give a total of 12 tanks and approximately 600 lbm; therefore, the modules could probably be launched and tested on one flight. Astronauts could set up the experiment, retrieve film packages, and monitor the experiment; but these services would not be essential since the experiment could probably be run automatically. If astronauts were present they would observe, using television, from the command module at some distance from the spinning S-IVB-SLA while the experiment was in progress.

VI. CONCLUSIONS

From the experiment as outlined in this study, valuable experimental data can be obtained in the area of cable-compartment-counterweight dynamics. Such data would include information in wobbling, cable dynamics, cable deployment techniques, damping devices, and effects of gravity gradient. This information could be applied directly in the generation of a three-dimensional model for a manned rotating space station. Figure 1 shows the range of data to be produced by the experiment compared to the existing data. The slosh data obtained are designed to fill in some of the gaps in current data and to establish the correct procedures for scaling future tests in both flight and ground facilities.

The primary advantage of the proposed facility over conventional facilities is that with a relatively small expenditure of propellant, a considerable amount of data can be obtained on both cable-compartment-counterweight dynamics and low g slosh phenomena. For example, with 20 pounds (9.072 kg) of APS propellant, a continuous acceleration spectrum can be obtained from 0.068 g's to .00033 g's. Since very little additional propellant would be required to maintain the rotation rate, the experimenter can, as time permits, fill in gaps or re-run tests in which questionable data were taken, thus allowing the investigator to make some preliminary analyses before completely abandoning the facility.

Also, the proposed facility makes maximum use of available hardware. Thus, it would represent a small investment, especially considering the quantity of data obtainable.

TABLE 1

STATE OF THE ART EXPERIMENTAL (GROUND TEST)

	TEST-TIME (SECONDS)	MODEL-SIZE (CENTIMETERS)	DATA
FREE FALL FACILITIES			
A. DROPTOWERS			
MSFC	4.6	15	VISUAL
N.A.A.	2.1	2.5	VISUAL
LEWIS	(DOUBLE	PASS PROPOSED)	
B. AIRCRAFT			
KC-135	32	———	VISUAL
BENCH TESTING			
SOUTHWEST RESEARCH INSTITUTE	∞	1.9	VISUAL & FORCE MEASURMENTS
OTHER			
ELECTROMAGNETIC			
LEWIS	SEVERAL MINUTES	2-3 INCHES	———
	(UNDER	DEVELOPMENT)	

TABLE 2

AVAILABLE FLIGHT DATA

	TYPE OF EXPERIMENT	DATA TAKEN
MERCURY (MA-7)	LIQUID ORIENTATION	VISUAL
CENTAUR-AC-4,8	COUPLED FREQUENCIES, MODE SHAPES, AMPLITUDES, & VEHICLE DYNAMICS	LIQUID/VAPOR SENSORS THERMOCOUPLES ACCELEROMETER DATA
WASP SHOT	LARGE AMPLITUDE IMPULSIVE SLOSH-FREQUENCIES, MODE SHAPES, AMPLITUDES, and DAMPING	VISUAL and ACCELEROMETER
AS-203	COUPLED FREQUENCIES, MODE SHAPES, AMPLITUDES, and VEHICLE DYNAMICS	VISUAL, LIQUID/VAPOR SENSORS, THERMOCOUPLE and ATTITUDE DATA

TABLE 3

STATE OF THE ART THEORETICAL

	FREQUENCIES and MODE SHAPES	FORCES and MOMENTS	DAMPING
CYLINDRICAL TANKS			
1. FREE OSCILLATIONS			
a. AXISYMMETRIC			
(i) LINEAR	FUNG-BENEDIKT (SOLUTIONS)	BENEDIKT (FORMULATED)	—
(ii) NON-LINEAR	—		
b. ANTI SYMMETRIC			
(i) LINEAR	SATTERLEE (SOLUTIONS)	BENEDIKT (FORMULATED)	—
(ii) NON-LINEAR	—		
2. FORCED OSCILLATIONS			
a. AXISYMMETRIC			
(i) LINEAR	FUNG (SOLUTIONS)	BENEDIKT (FORMULATED)	—
(ii) NON-LINEAR	—	—	
b. ANTISYMMETRIC			
(i) LINEAR	BENEDIKT (FORMULATED)	BENEDIKT (FORMULATED)	
(ii) NON-LINEAR	—	—	
SPHERICAL TANKS	—	—	—

TABLE 4

TEST PROGRAM

TEST	g/g_o	TIME ~ MIN.	BOND NUMBER MAX.	BOND NUMBER MIN.
1	.0068	33	55	12
2	.0050	37	39	9
3	.0030	47	27	5.2
4	.0020	58	16	3.5
5	.0010	79	8	1.7
6	.0005	107	4	.90
7	.00037	121	3	.67

TOTAL: 8 HRS.

TABLE 5

FORCED SLOSHING

BOND NUMBER 55 (g/g_o = .0068)

MODULE I

TANK I UNBAFFLED CYLINDER 15 CM. (6 IN.) RAD.

FLUID ETHYL ALCOHOL

RUN	FORCING FREQUENCY~CPS	FORCING AMPLITUDE	DURATION (SEC)
1	.100	.18 CM. (.0072 IN.)	140
2	.120	↓	↓
3	.130	↓	↓
4	.143 (NATURAL)	↓	↓
5	.150	↓	↓
6	.160	↓	↓
7	.180	↓	↓

33 MIN.

AVAILABLE EXPERIMENTAL DATA

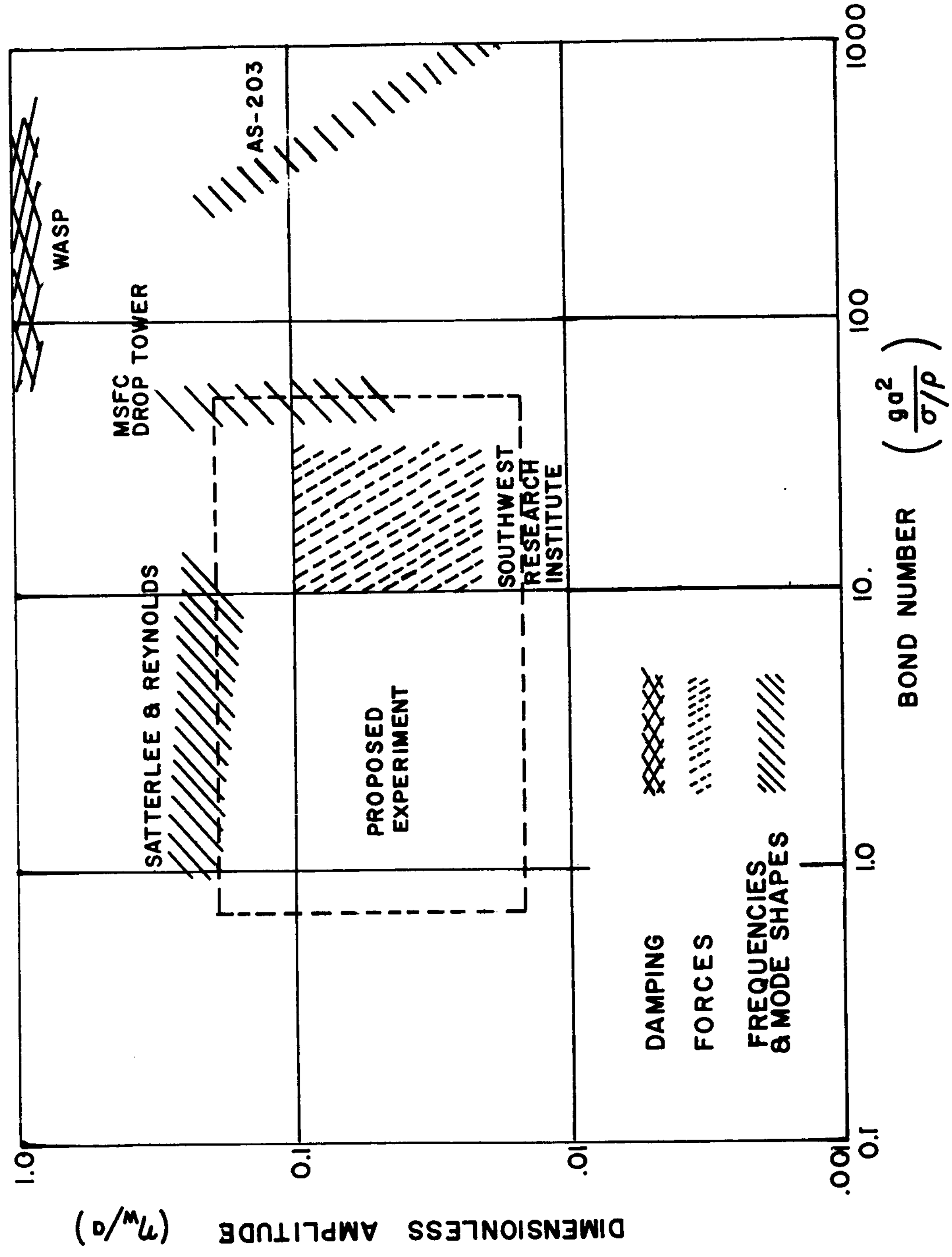


FIG. 1

BASIC CONFIGURATION

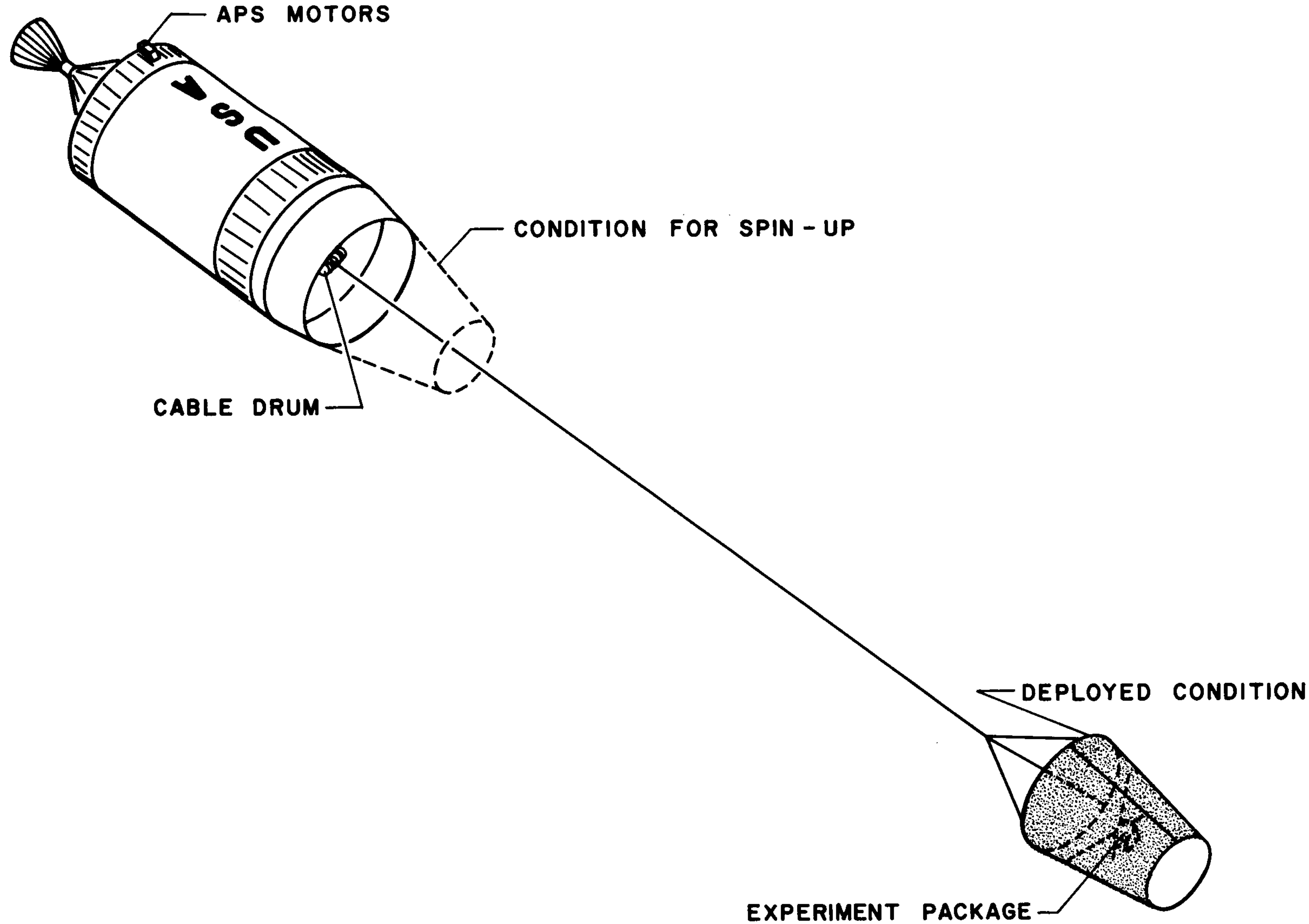


FIG. 2

EXPERIMENT LOCATION

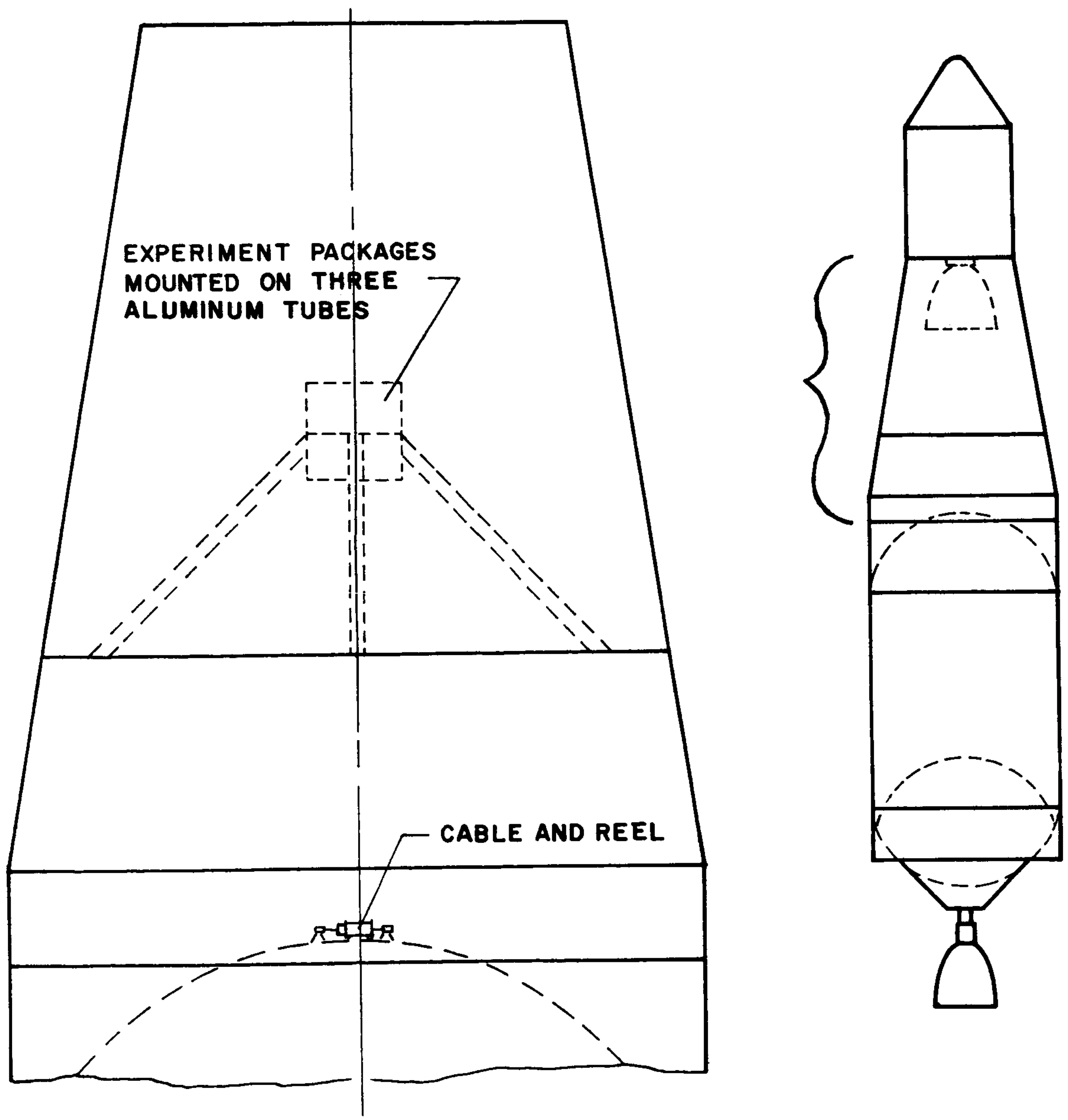
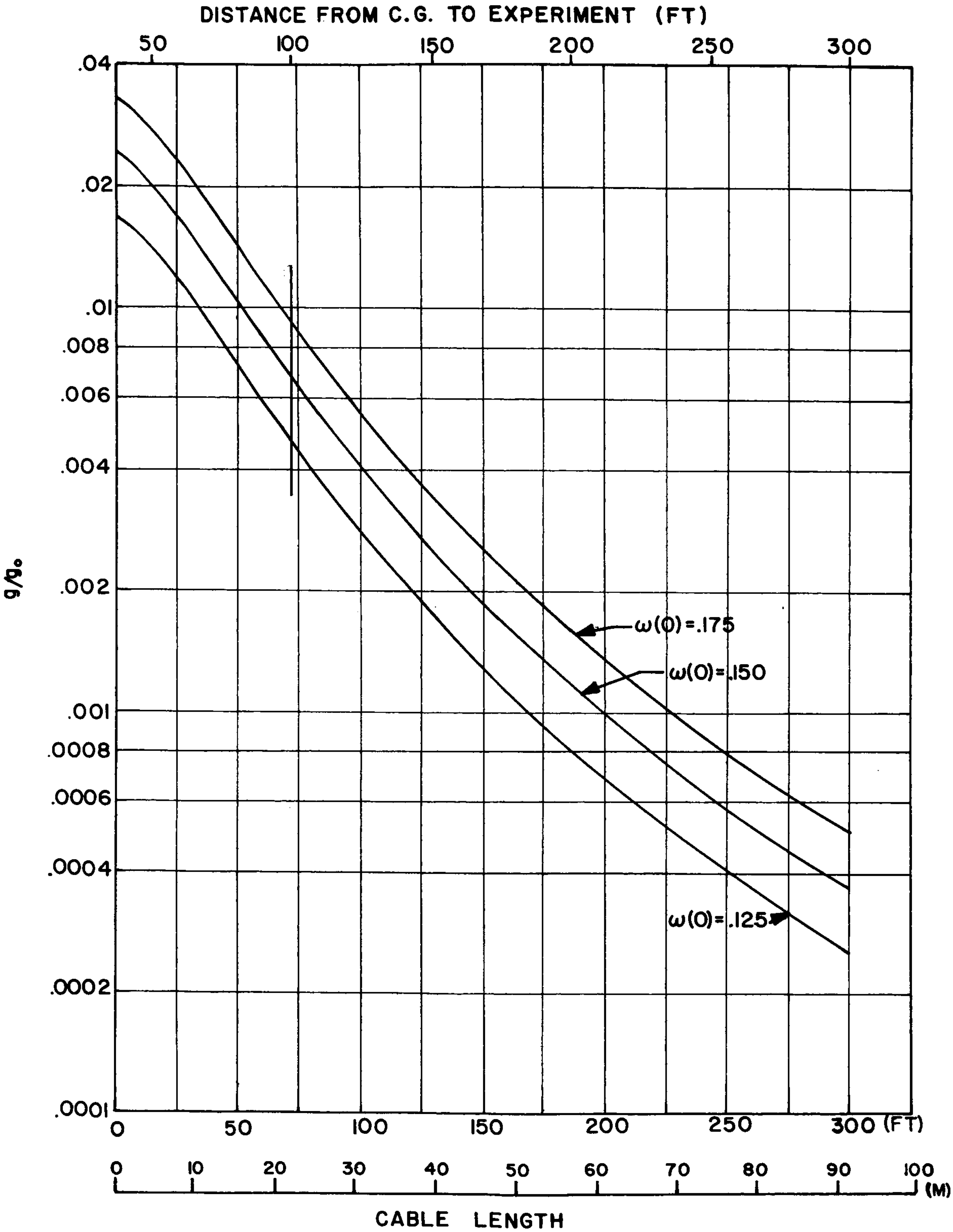


FIG. 3



DISTANCE FROM C.G. TO EXPERIMENT (FT)
50
100
150
200
250
300
.04
.02
.01
.008
.006
.004
.002
.001
.0008
.0006
.0004
.0002
.0001
g/g₀
ω(0)=.175
ω(0)=.150
ω(0)=.125
0
50
100
150
200
250
300 (FT)
0
10
20
30
40
50
60
70
80
90
100
(M)
CABLE LENGTH

FIG. 4

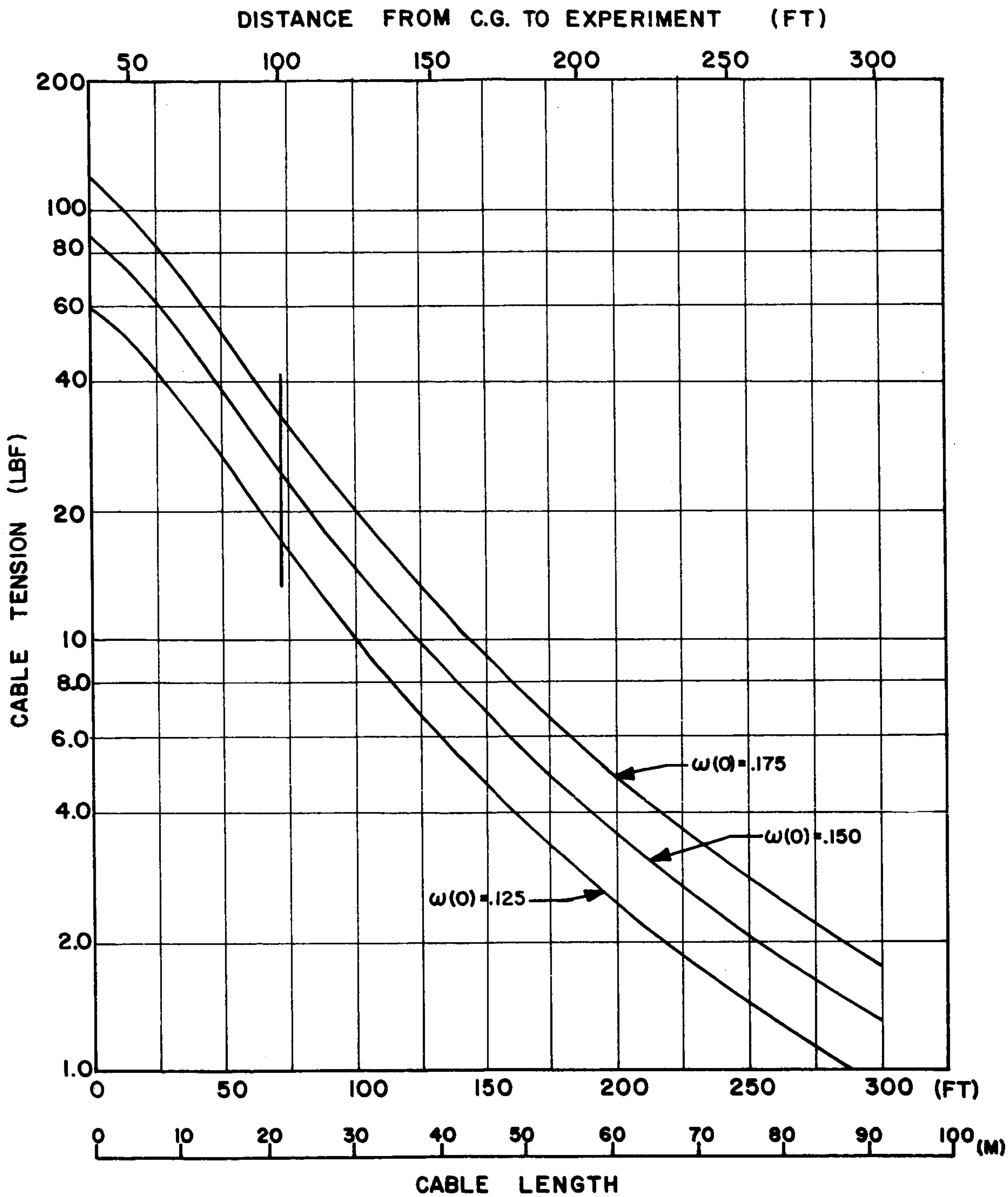

DISTANCE FROM C.G. TO EXPERIMENT (FT)
50
100
150
200
250
300
200
100
80
60
40
20
10
8.0
6.0
4.0
2.0
1.0
CABLE TENSION (LBF)
ω(0)=.175
ω(0)=.150
ω(0)=.125
0
50
100
150
200
250
300 (FT)
0
10
20
30
40
50
60
70
80
90
100 (M)
CABLE LENGTH

FIG. 5

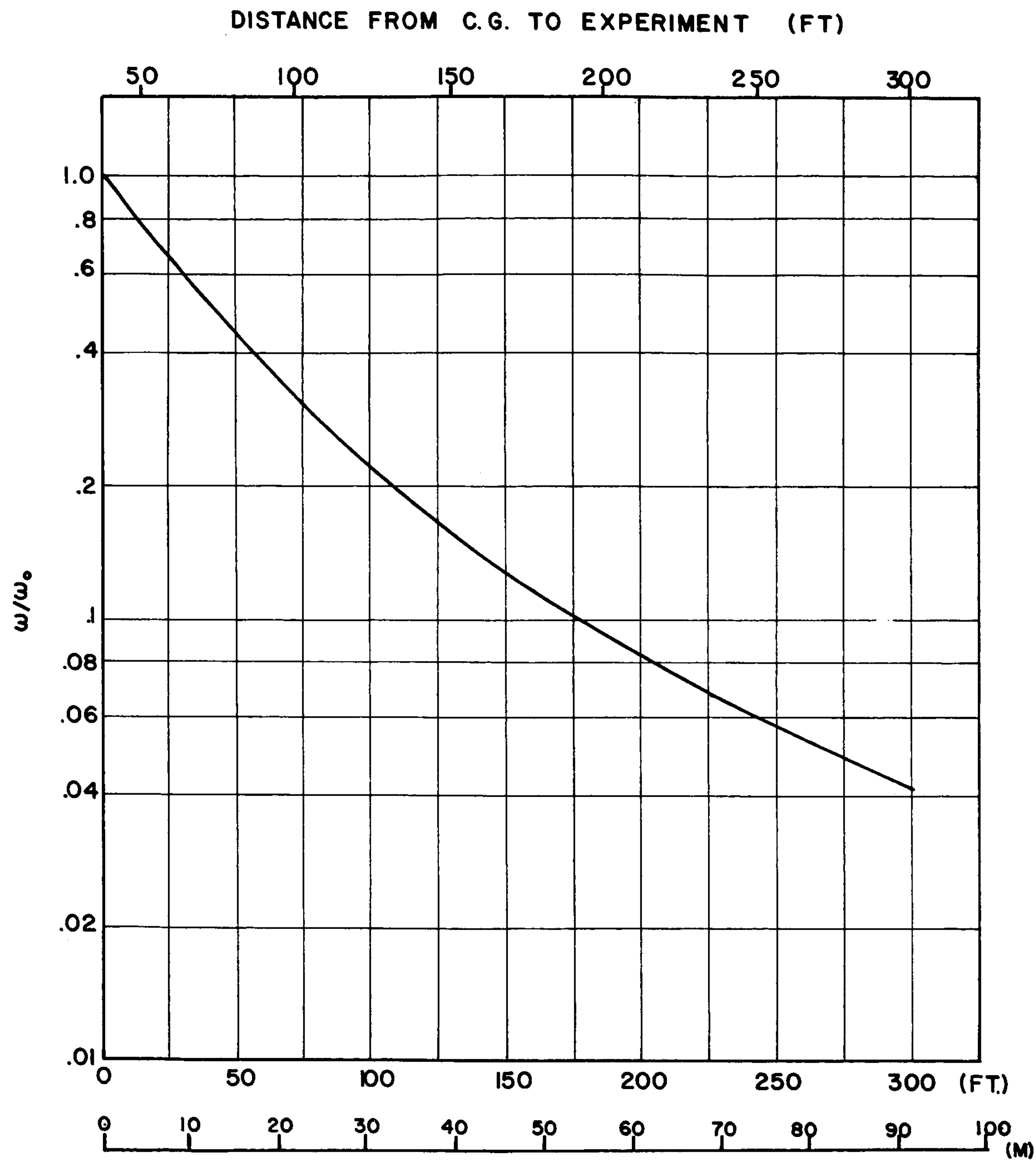
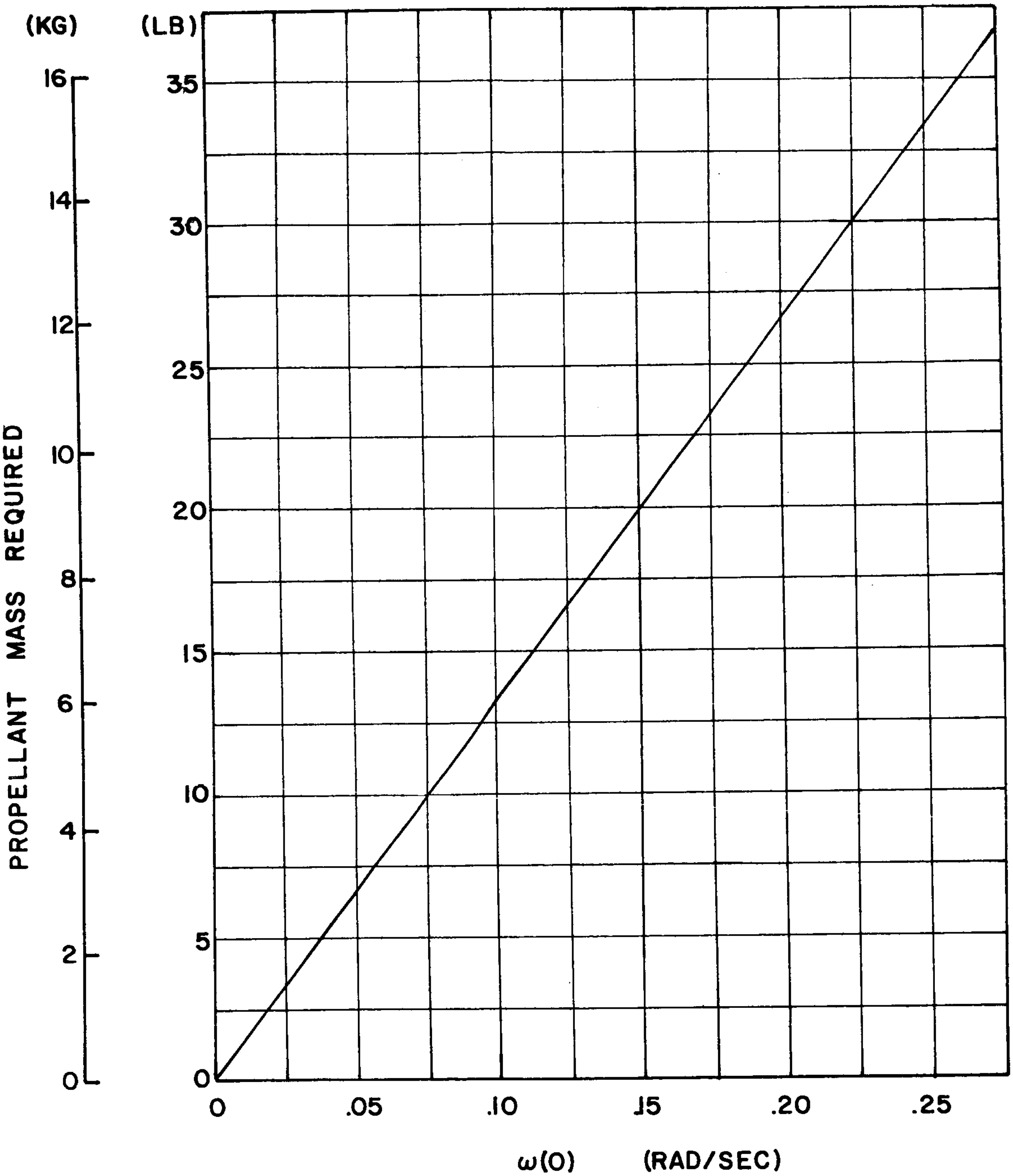

DISTANCE FROM C.G. TO EXPERIMENT (FT)
50
100
150
200
250
300
1.0
.8
.6
.4
.2
.1
.08
.06
.04
.02
.01
ω/ω₀
0
50
100
150
200
250
300 (FT.)
0
10
20
30
40
50
60
70
80
90
100
(M)
CABLE LENGTH

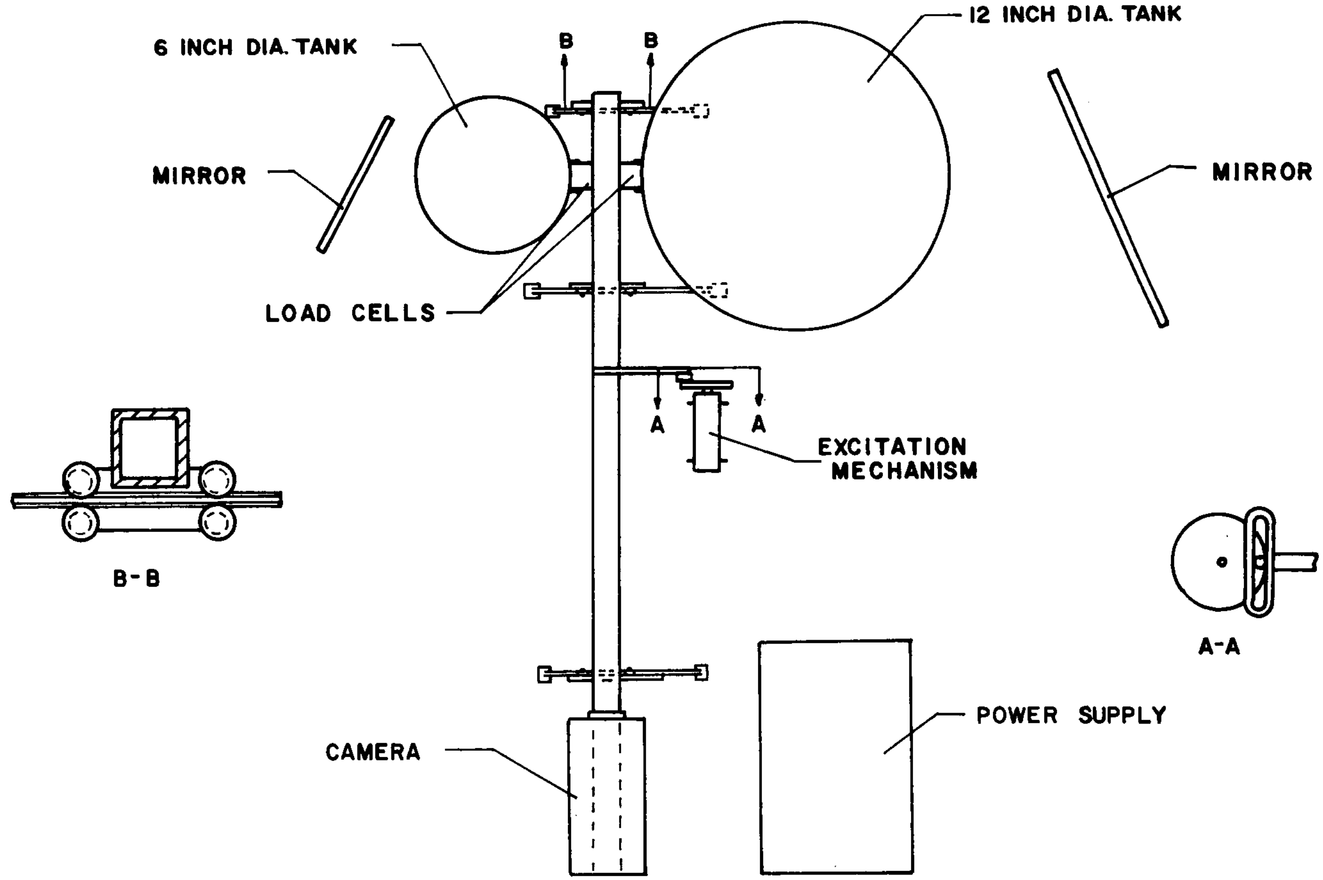
FIG. 6



(KG)
(LB)
16
14
12
10
8
6
4
2
0
35
30
25
20
15
10
5
0
PROPELLANT MASS REQUIRED
0
.05
.10
.15
.20
.25
ω(0) (RAD/SEC)

FIG. 7

EXPERIMENT PACKAGE



APPROXIMATE WEIGHT = 100 LB.
OVERALL DIMENSIONS = 36" X 36" X 18"

ONE EXPERIMENT PACKAGE REQUIRED FOR BAFFLED TANKS AND ONE FOR UNBAFFLED.

FIG. 8

POSSIBLE METHODS OF SLOSH EXCITATION

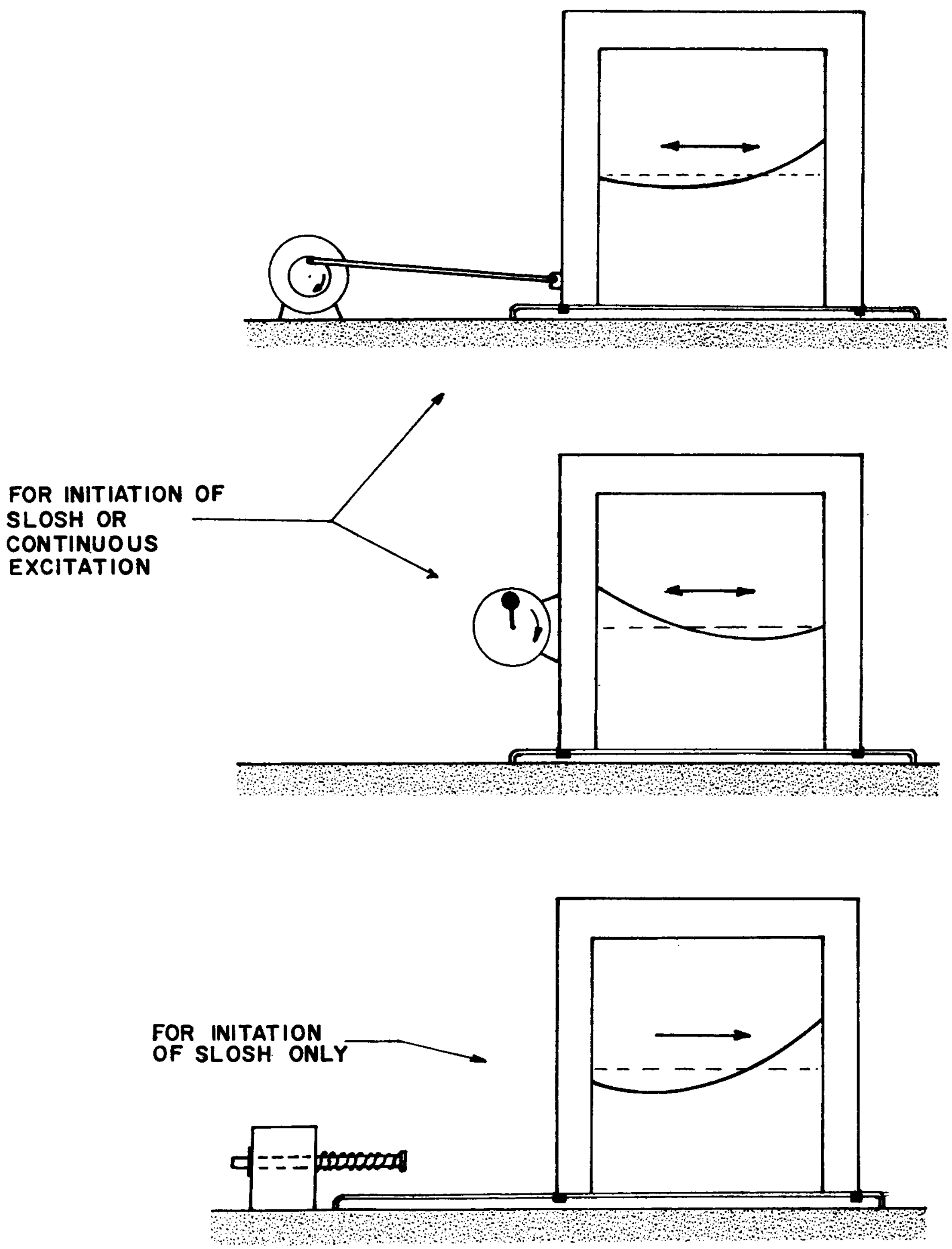
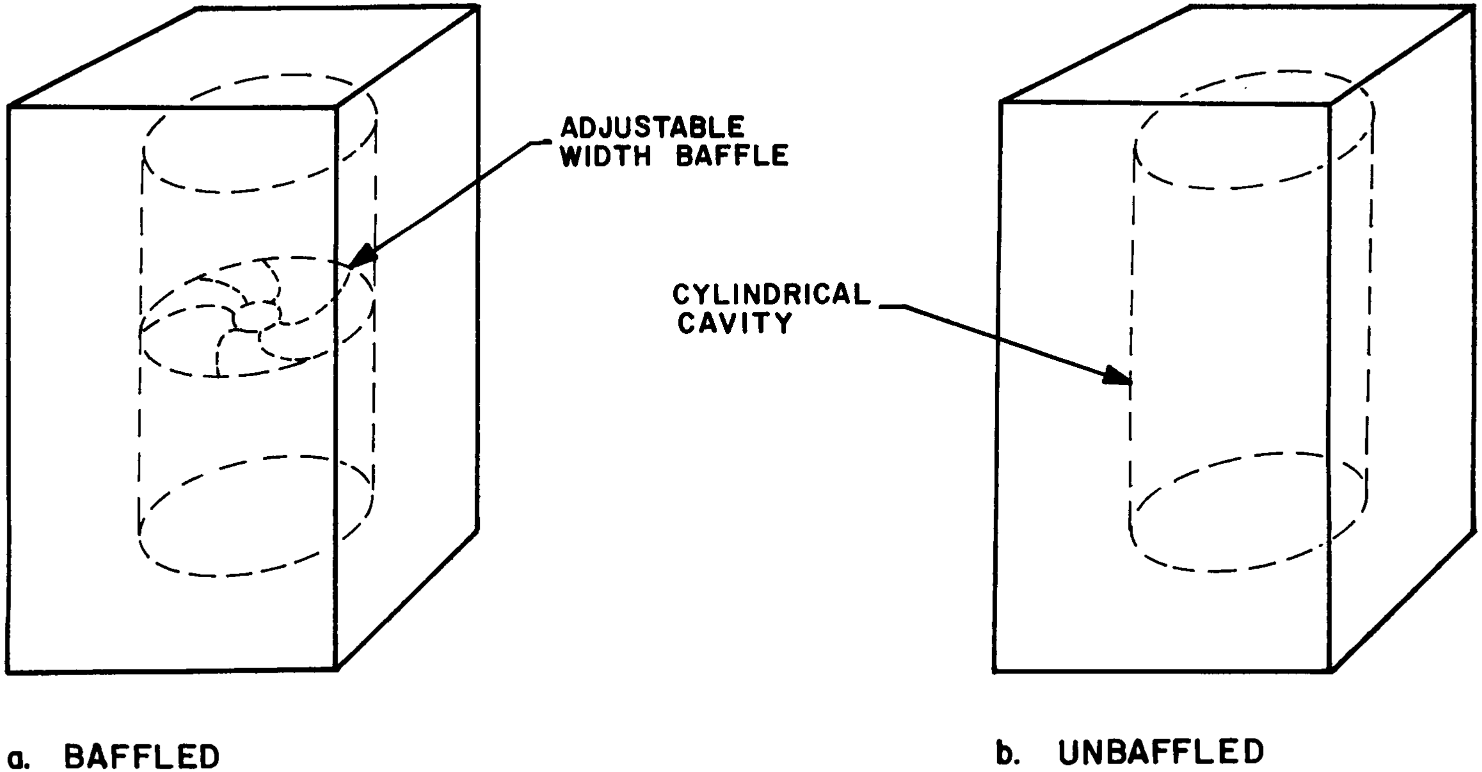
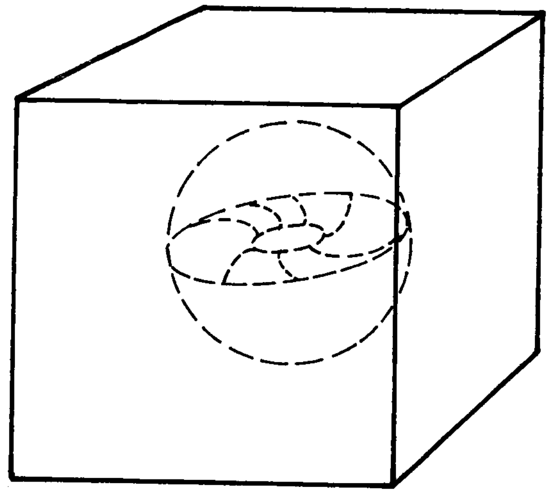


FIG. 9



CYLINDRICAL TANKS

FIG. 10



SPHERICAL TANKS

FIG. 11

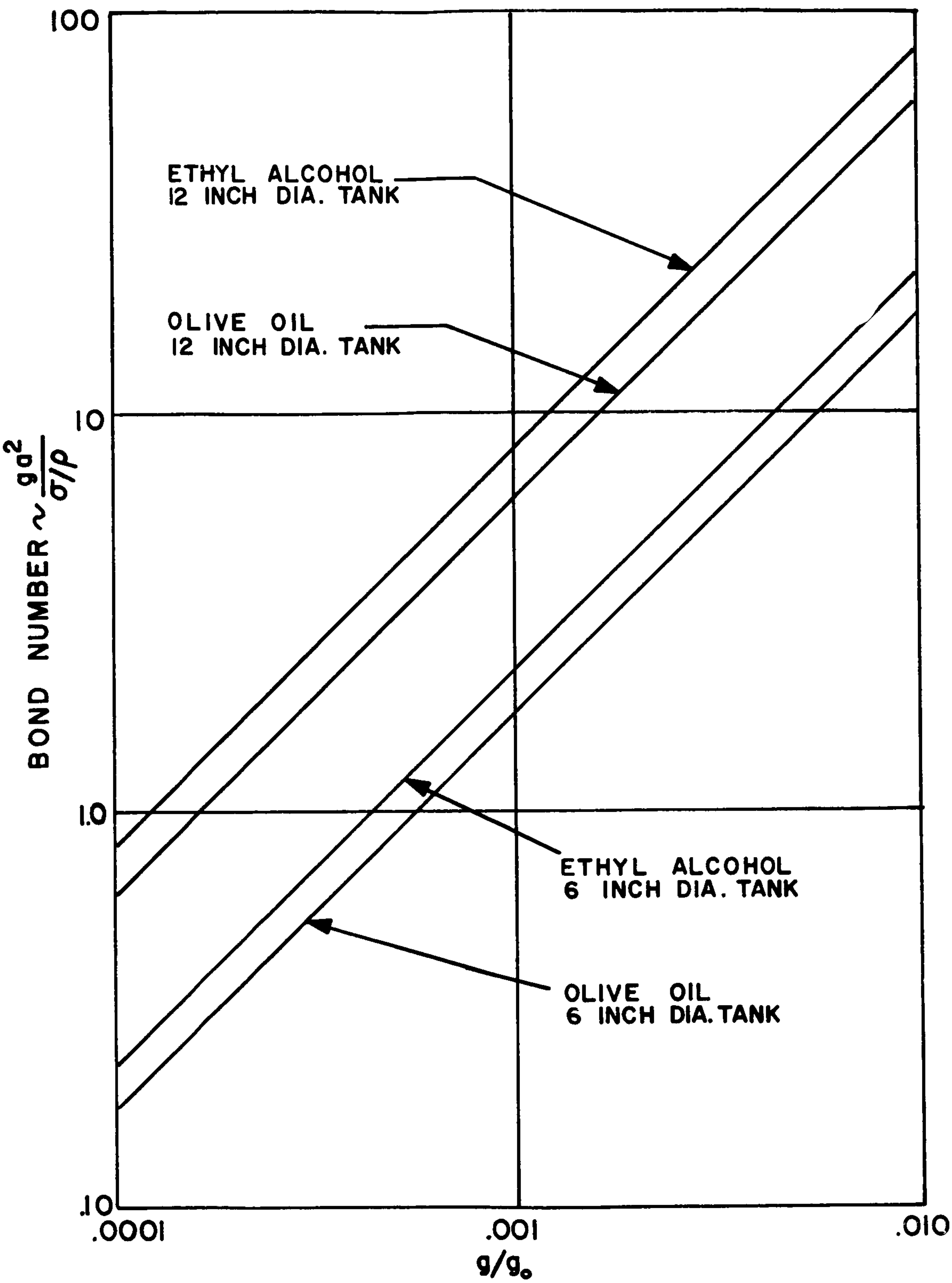
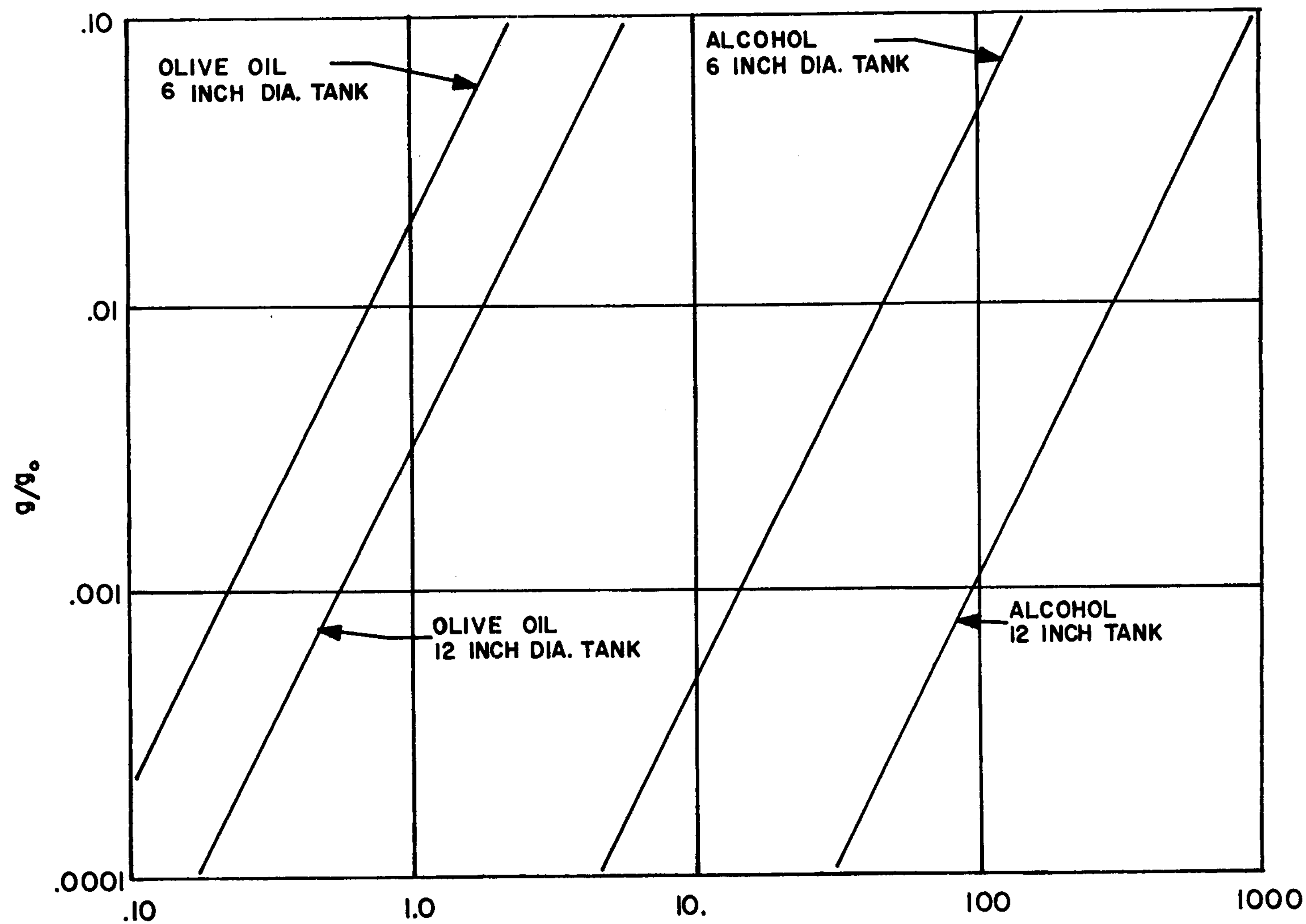

ETHYL ALCOHOL
12 INCH DIA. TANK
OLIVE OIL
12 INCH DIA. TANK
ETHYL ALCOHOL
6 INCH DIA. TANK
OLIVE OIL
6 INCH DIA. TANK
BOND NUMBER $\sim \frac{ga^2}{\sigma/\rho}$
100
10
1.0
.10
.0001
.001
.010
g/g_o

FIG. 12



.10
.01
.001
.0001
OLIVE OIL
6 INCH DIA. TANK
OLIVE OIL
12 INCH DIA. TANK
ALCOHOL
6 INCH DIA. TANK
ALCOHOL
12 INCH TANK
.10
1.0
10.
100
1000
REYNOLDS NUMBER

FIG. 13

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AN ORBITAL FACILITY FOR LOW GRAVITY FLUID MECHANICS EXPERIMENTS

by H. E. Worley, F. M. Bugg, and H. J. Buchanan

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This document has also been reviewed and approved for technical accuracy.

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